The decision to implement the WFIRST mission will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

The WFIRST Coronagraph Instrument

EMCCD Technology Advancements for the WFIRST Coronagraph

Patrick Morrissey, JPL Flight Instrument Detectors and Camera Systems

Jet Propulsion Laboratory
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WFIRST Coronagraph Camera Team

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- **WFIRST is the Wide Field Infrared Survey Telescope**, a major new NASA observatory set to fly in the mid 20s. Its prime science mission is to study supernovae and gravitational (weak and micro) lensing
- WFIRST will also fly a **Coronagraph Instrument (CGI)** designed to make direct images and spectra of planets around nearby stars
- The CGI is a ***technology demonstration mission*** that will showcase precision pointing, active wavefront control, and optical photon counting detectors in space for the first time.

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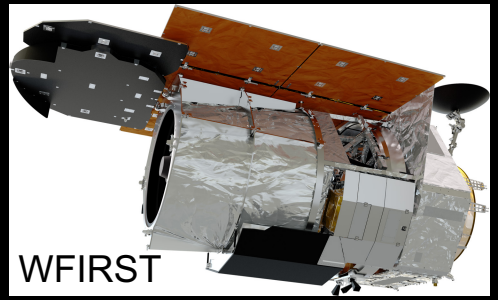
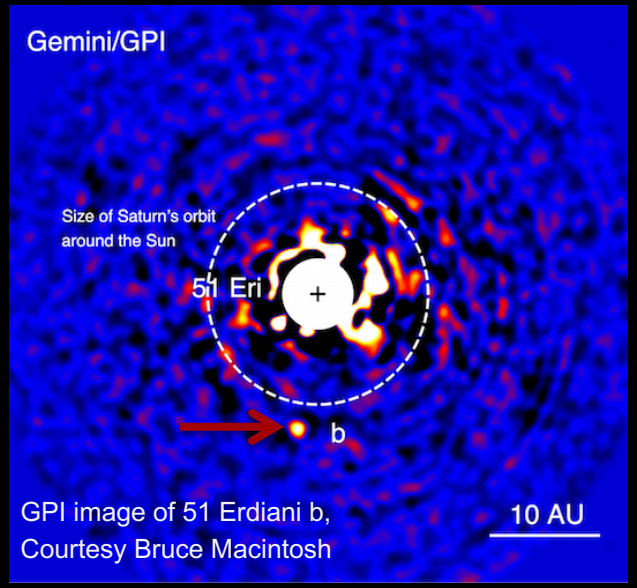
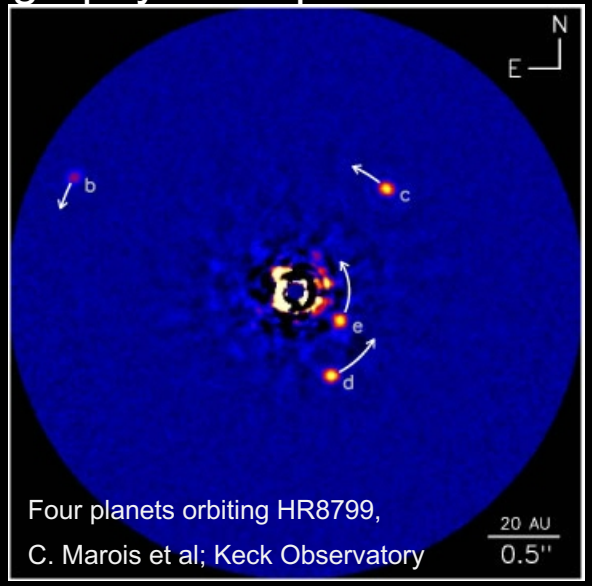


Ground-based Coronography Examples



GPI image of 51 Erdiani b,
Courtesy Bruce Macintosh



Four planets orbiting HR8799,
C. Marois et al; Keck Observatory

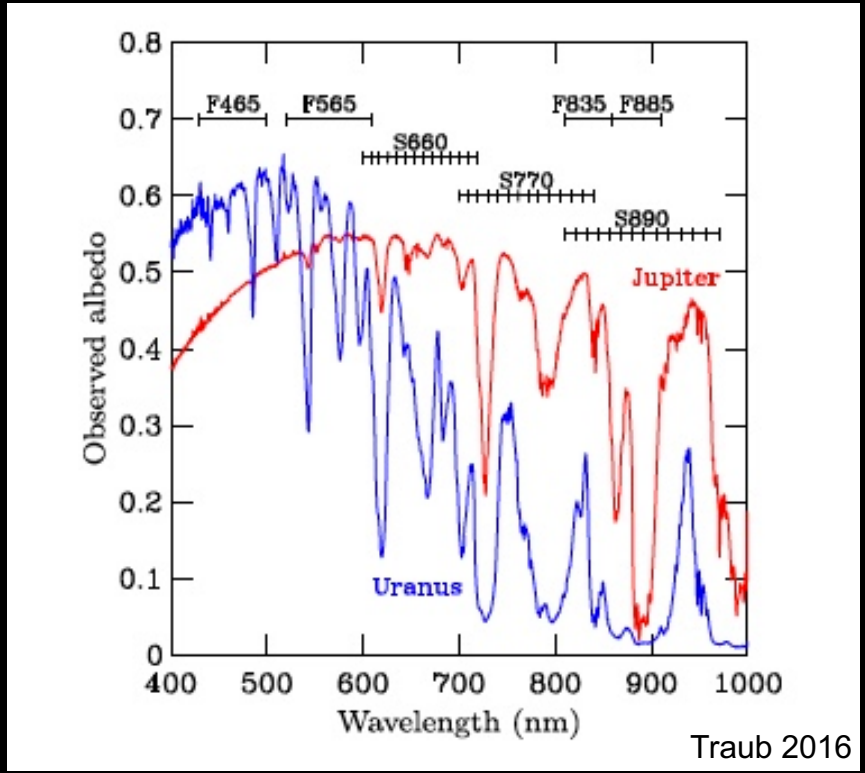
The exciting field of exoplanet discovery and characterization is successfully identifying many new planetary systems. Most are too far to be directly imaged. **The few planets that have been directly imaged from the ground are young, large, hot, and far from their stellar hosts.**

The WFIRST CGI will demonstrate technology necessary to detect **planets that are similar to the ones in our own solar system.**

For reference a **Jupiter-like system** at a distance of 50 ly from us would present a **maximum star-planet separation of 0.3" with a dynamic range of ~10^9.**

Requirements

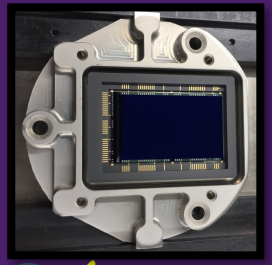
- ✓ Optical/red sensitivity to detect spectral features of interest
- ✓ Extremely low noise to enable faint detection
- ✓ Wide dynamic range to accommodate coronagraph operations
- ✓ High speed readout for wavefront sensing
- • Rad-hard – JPL has invested significantly in technology development in this area.



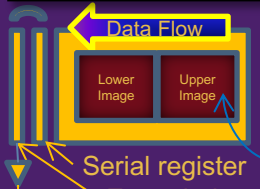
Traub 2016

EMCCD Pulse Height Distribution

Teledyne-e2v EMCCD Technology

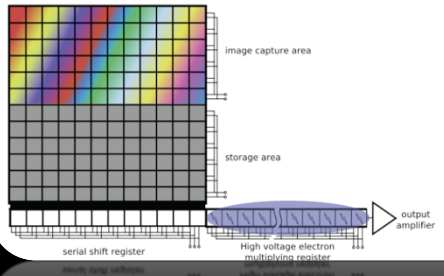


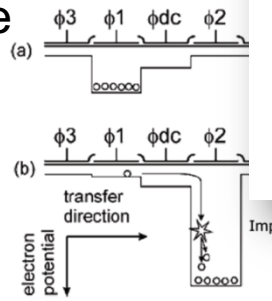
An **extended serial register** operating at elevated voltage (~50V) amplifies signals well above the level of the read noise, enabling high QE CCD imaging and **zero read noise** photon counting.

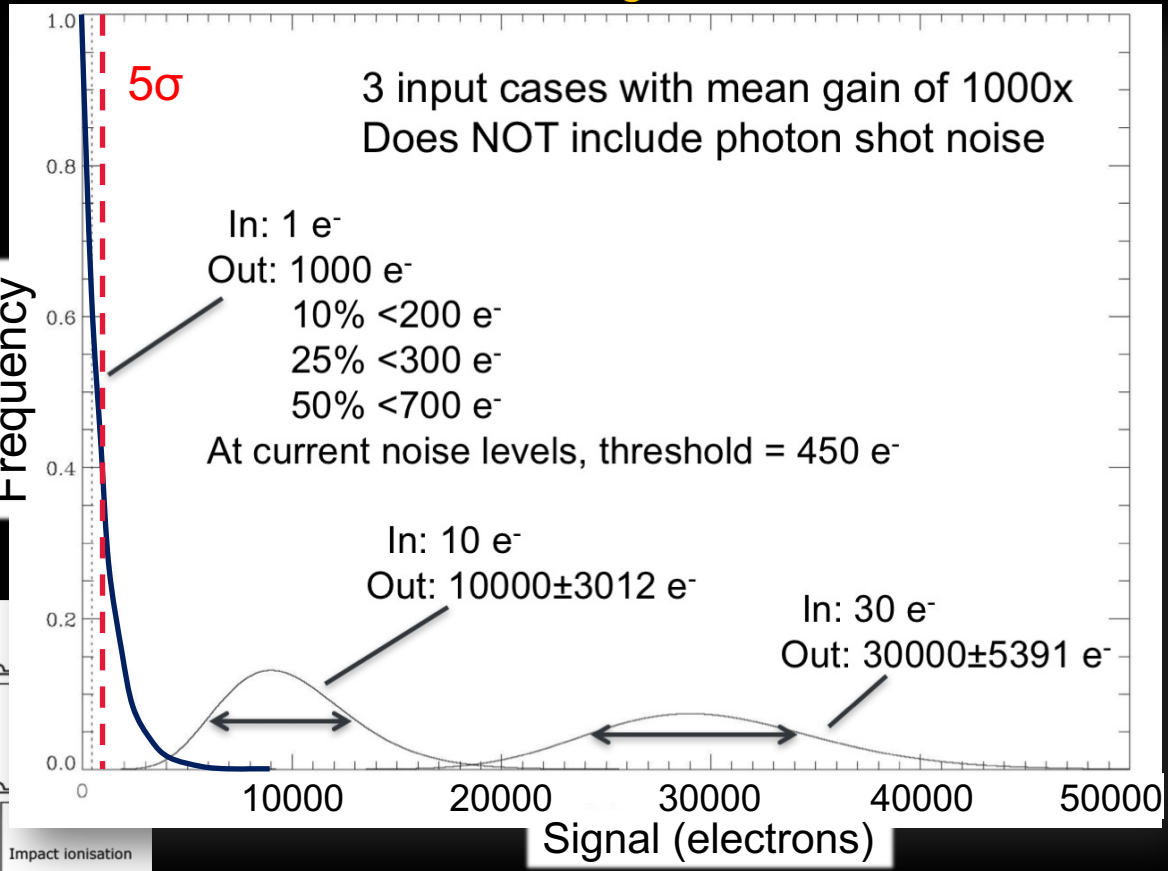


Functional diagram

EMCCD Architecture



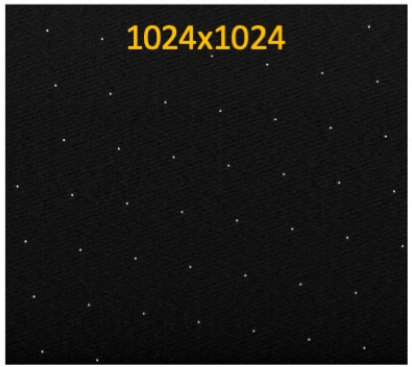


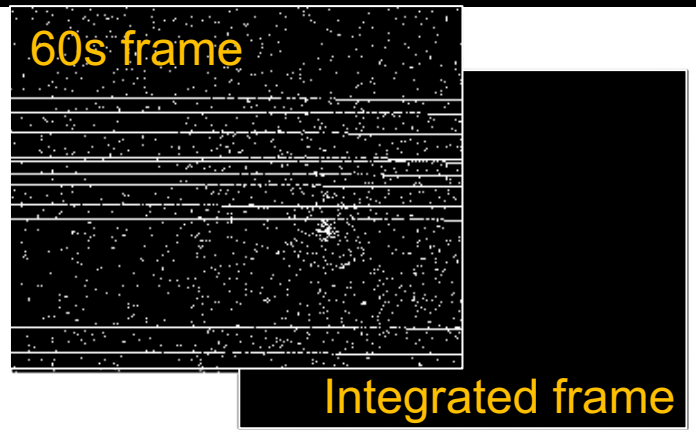


The “gain” is the weighted mean of the signal

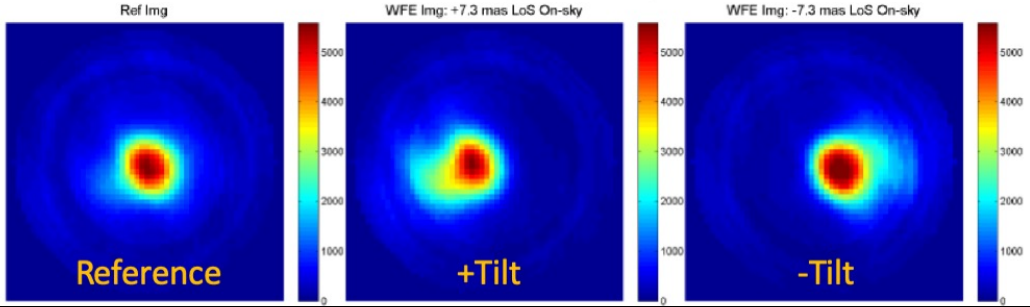
Planned EMCCD Modes

1) Acquisition: Bright targets at unity gain "normal mode"



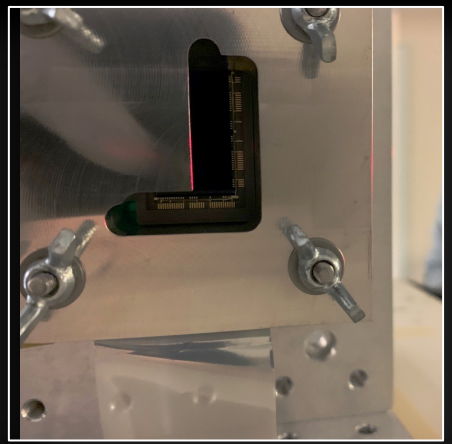


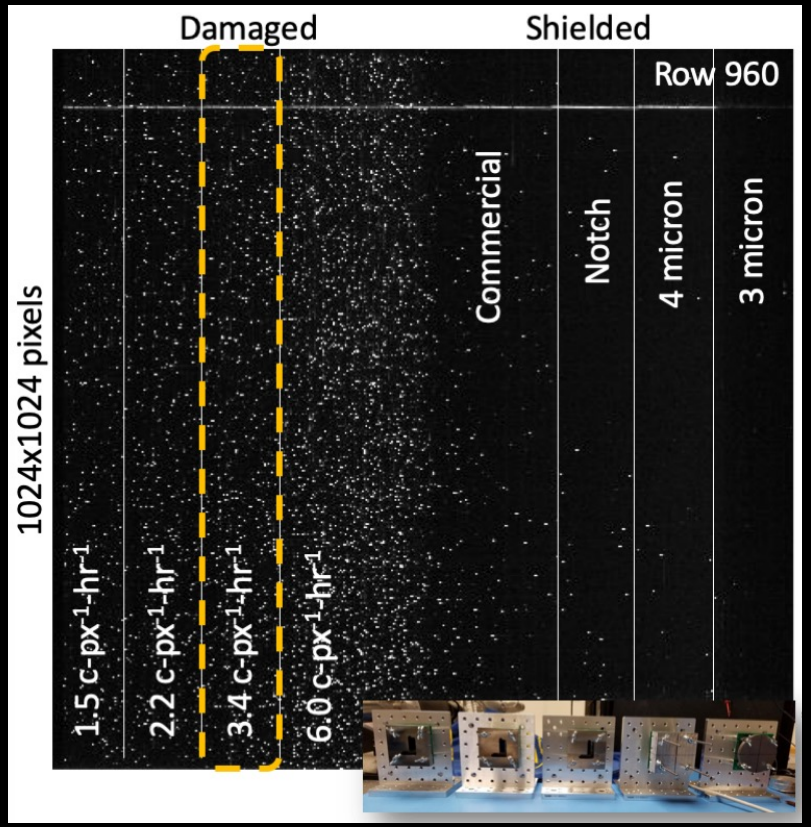
3) LOWFS: Low Order Wavefront Sensor 1000 fps "analog mode"



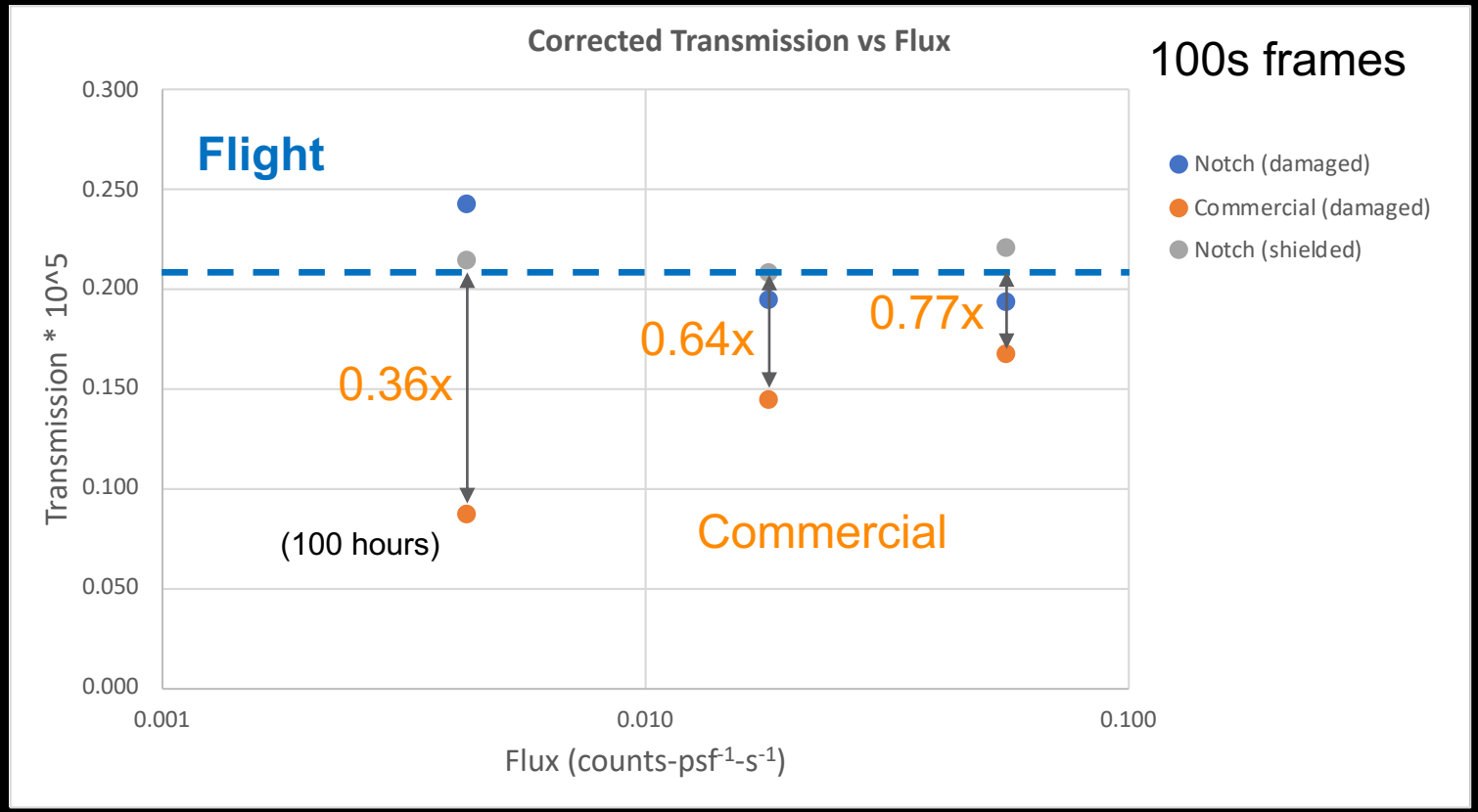
Technology Development at Teledyne-e2v

- Flight prototype EMCCDs were irradiated with a flight-like dose of 85 and 150 MeV protons at Loma Linda Medical Center
- The new designs significantly improve performance with respect to dark current and low light level charge transfer
- We have chosen a design that meets the requirements of both the wavefront sensor and science sensor applications.
- A key result of the program is that frame times must be sufficiently long to provide signal charge to fill traps in photon counting mode.





dQE vs Flux


Corrected Transmission vs Flux
100s frames
Flight
Commercial
0.36x
0.64x
0.77x
(100 hours)
Notch (damaged)
Commercial (damaged)
Notch (shielded)
Transmission * 10^5
0.300
0.250
0.200
0.150
0.100
0.050
0.000
0.001
0.010
0.100
Flux (counts-psf-1-s-1)

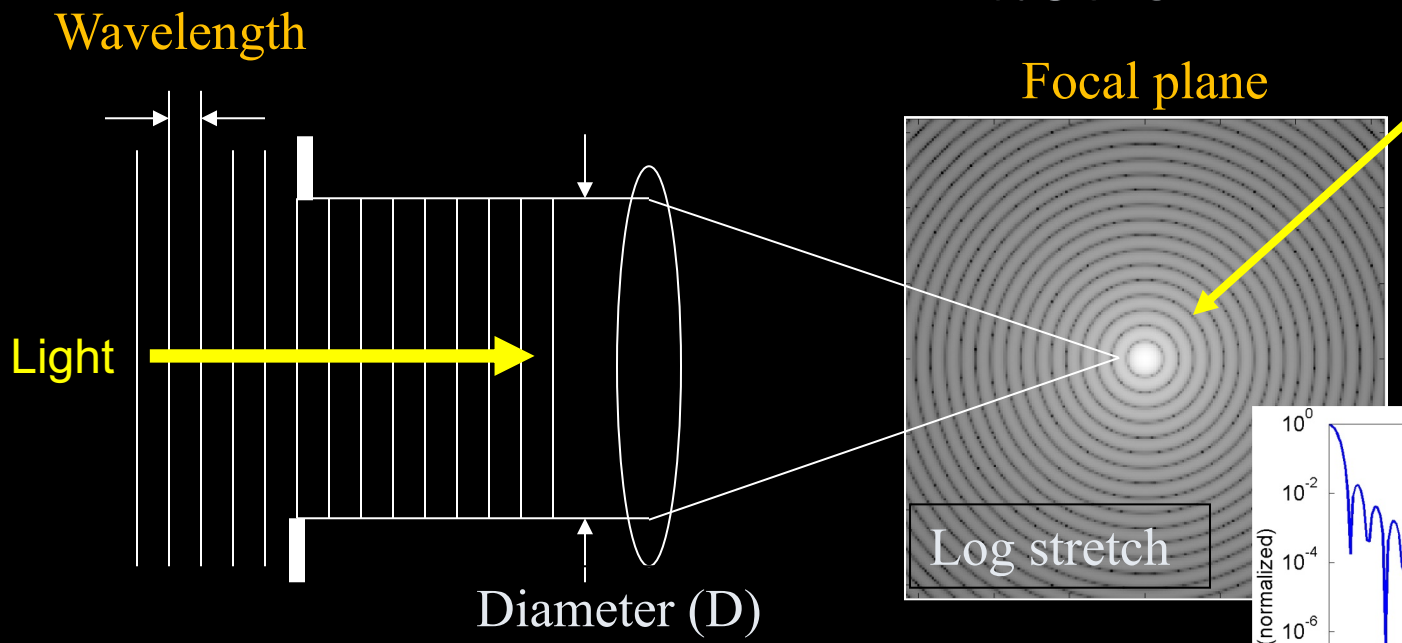
Summary

- The WFIRST Coronagraph Instrument is a demanding technology demonstration that is planned to advance the state-of-the-art for future large missions to directly image habitable planets.
- The Coronagraph Instrument passed PDR in September 2019 and has now entered Phase C.
- We will deliver two identical cameras to the coronagraph for the science and wavefront sensing applications. Each camera system is comprised of:
  1. An ESA-contributed, radiation-hardened EMCCD from Teledyne-e2v (UK)
  2. An ABB/NuVu procured camera controller (Canada)
  3. A JPL-build optomechanical radiation shield assembly
- The EMCCD program has been on-going for several years.
  - Phase 1: Characterize the commercial EMCCD in the radiation environment. 2016-17.
  - Phase 2: Contract Teledyne-e2v to implement modifications to the commercial design that could improve lifetime. Characterize the modified devices and choose the optimal combination for flight. 2018.
    - Flight designs represent a significant performance improvement (~3x) over the commercial EMCCD in the radiation environment.
  - Phase 3: Develop flight packaging and perform risk-reducing environmental tests (ESA funded). 2019.
  - Phase 4: Flight EMCCD development program (ESA funded). 2020-
- EDU cameras are being fabricated in 2020 and FM cameras are planned in 2021.

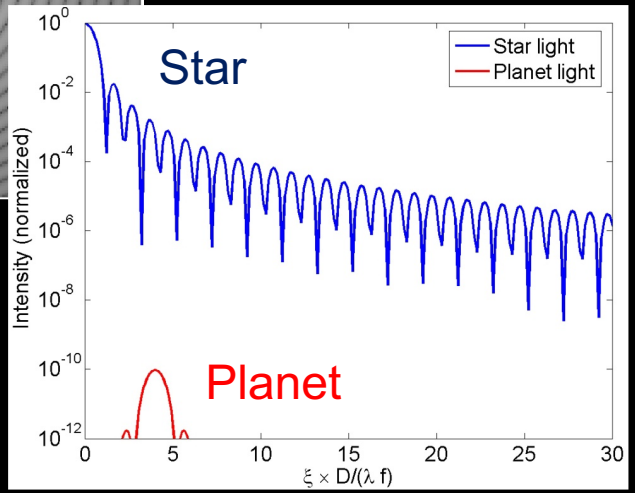

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

Backup

Diffraction



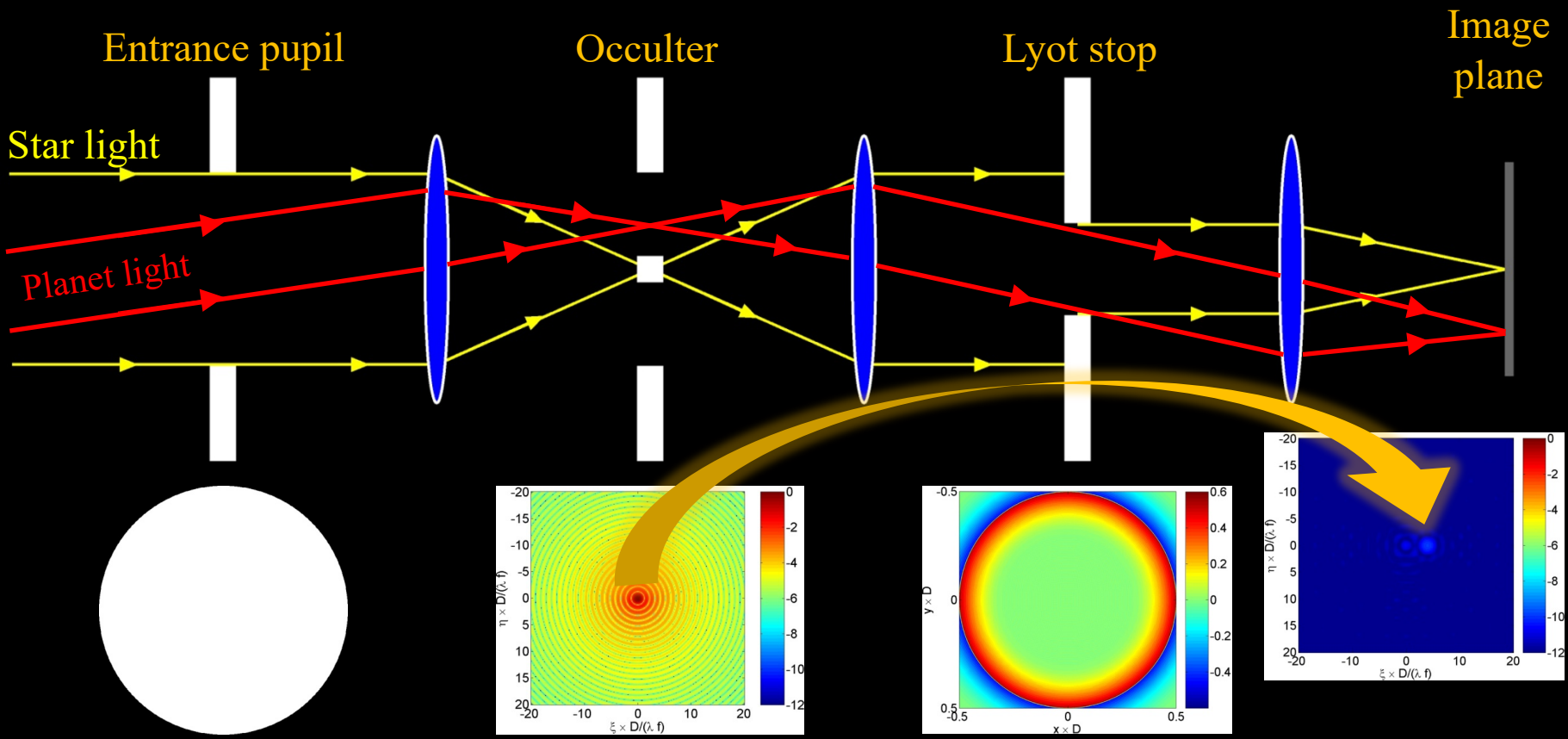
The planet is hidden in here, and would be over a million times dimmer)



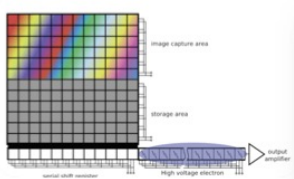
Diffraction is a big problem for direct exoplanet detection.

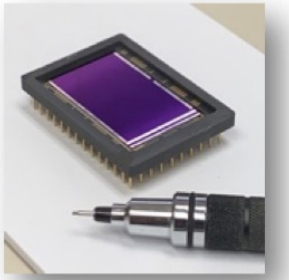
- Bigger telescopes help
- Coronagraphs suppress the diffraction

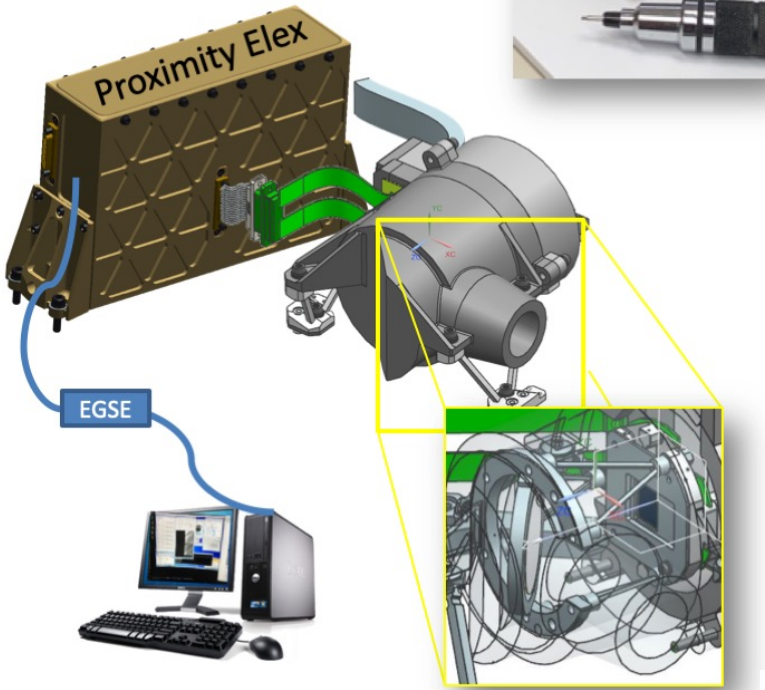
The Lyot Coronagraph



- **The CGI Camera Subsystem comprises two nominally identical EMCCD cameras with different applications:**
  - A photon counting **Exoplanetary Camera** for target acquisition, direct imaging and spectroscopy
  - A low latency **Wavefront Sensing Camera** for high frame rate imaging
- **A camera system includes:**
  - **ESA-contributed** EMCCD
    - 1kx2k, available photon counting
  - **JPL-procured** FPGA controller
    - Includes GSE C&DH (Windows)
  - **JPL-built** optomechanical radiation shield assembly

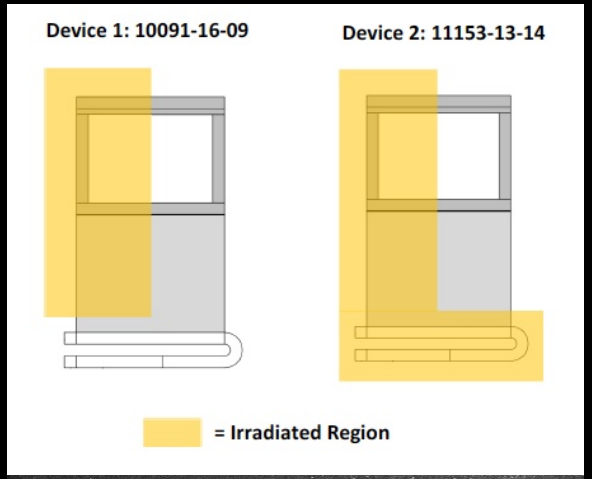


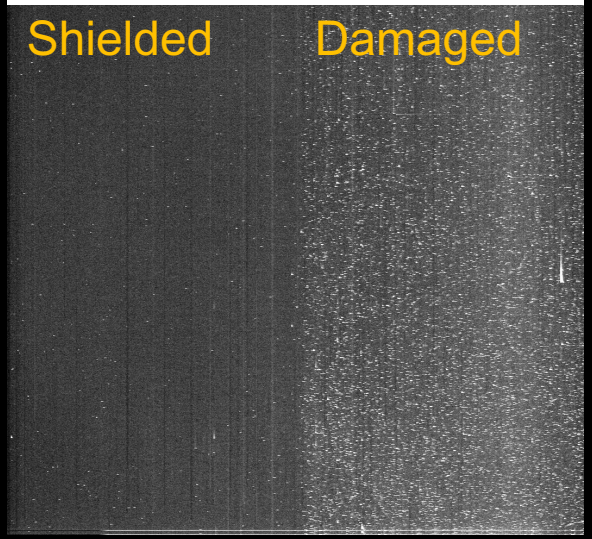




The WFIRST Radiation Test Program

- The camera team has characterized the low flux sensitivity of radiation-damaged EMCCDs operating in photon counting mode.
  - The low noise performance of the EMCCD provides a performance advantage over almost any other type of detector.
- We have engaged the Centre for Electronic Imaging, Open University (UK) to help with testing and evaluation.
  - Commercial EMCCDs have been irradiated by protons to a 5 year flight-like dose.
  - Separate cold and warm irradiations (cold is worse)
  - We are operating radiation damaged EMCCDs in our lab at JPL using a commercial controller.
- The commercial EMCCD is radiation sensitive (as are all CCDs) but has margin on the technology requirements of the coronagraph.
  - We have contracted Teledyne-e2v to develop several variants of the commercial EMCCD that will be more robust to radiation, will address the effect of cosmic ray tails generated in the gain register, and will reduce latency for the LOWFS application.
  - **We are evaluating the LOWFS-optimized devices in the lab now, and expect to receive and test the science variants in the fall of 2018.**

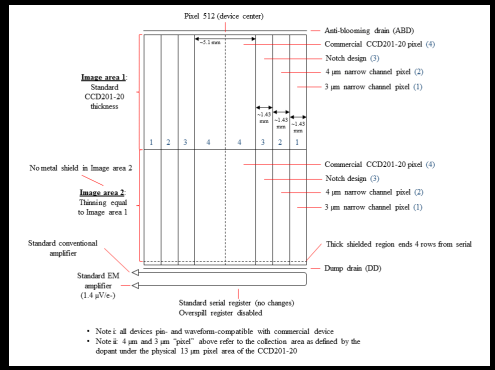


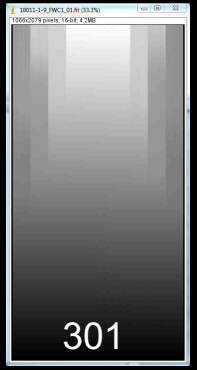


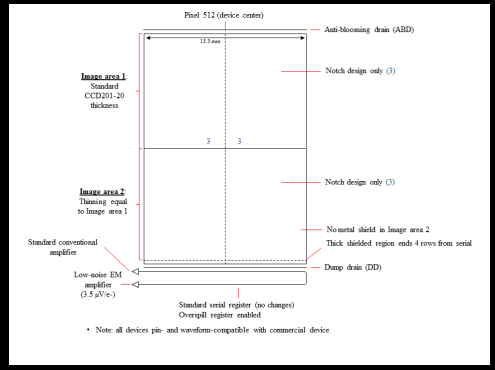
Technology Development at Teledyne-e2v

- We have funded a program with Teledyne-e2v to produce radiation-hardened EMCCD detectors for flight that are based on the CCD201.
  - Type A (Wavefront sensor test):
    - Removes store shield
  - CCD301:
    - Removes store shield
    - Implements several different column widths to minimize transfer effects due to trap damage
  - CCD302:
    - Removes store shield
    - Implements a single “notch channel” design in the image area
    - Adds an overspill feature to the gain register
    - Implements a new 3T output stage to reduce noise with higher output loads
- These devices were evaluated in 2018 in support of a technology “Decision Point” in April 2019.

Wafer Probe







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